Perturbative QCD at the Tevatron and the LHC

June 2005

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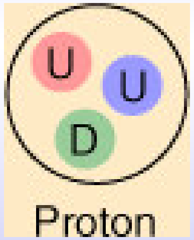
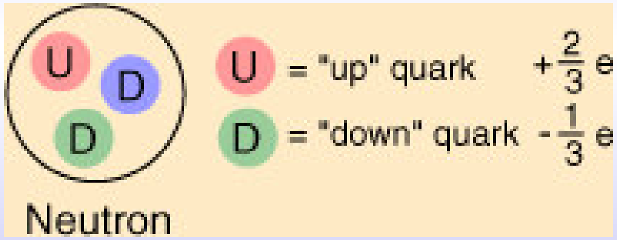
Outline

- Introduction to hadron collider physics
- Making predictions using perturbative Quantum Chromodynamics
- Overview of a next-to-leading order tool, MCFM
- Examples of predictions from MCFM
  - ⋆ The production of vector bosons and jets
  - ⋆ Jets containing bottom quarks
  - ⋆ Single top quark production
- Summary

Motivation

- To investigate the building blocks of matter and the forces that bind them together.
- For 20 years, thanks to experiments at SLAC (Stanford, California) we've known that we can think of protons and neutrons as sets of quarks, bound together by a sea of gluons.

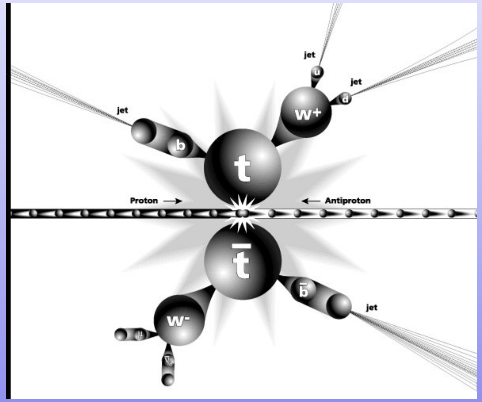




- To investigate such small distance scales requires probes with large energy, since the de Broglie wavelength should be small, $\lambda = hc/E$. This sets a natural scale for HEP of $\mathcal{O}(1)$ GeV, corresponding to a proton radius of $\mathcal{O}(1)$ fm.
- To investigate ever-smaller substructure, we are driven to higher energies.

Particle collisions

- Produce two beams of relatively light particles (electrons, positrons, (anti-)protons with $m \approx 0$) and accelerate them to high energies, E.
- Collide the beams, so that interactions can occur. The energy available to produce new heavy objects is $2E$=$\sqrt{s}$, the centre-of-mass energy.
- If all the energy of the collision is used to create a heavy particle, then this is the mass of the heaviest particle that can be produced.



top quark mass is $m_t = 175$ GeV, so pair production requires that $\sqrt{s} > 350$ GeV

HEP colliders

CERN, Geneva: e^+e^- collider

LEP-I : $\sqrt{s} = 91$ GeV $(= M_{Z^0})$
LEP-II : $\sqrt{s}$ up to 209 GeV

To start in 2007:

LHC: pp collider
with $\sqrt{s} = 14$ TeV

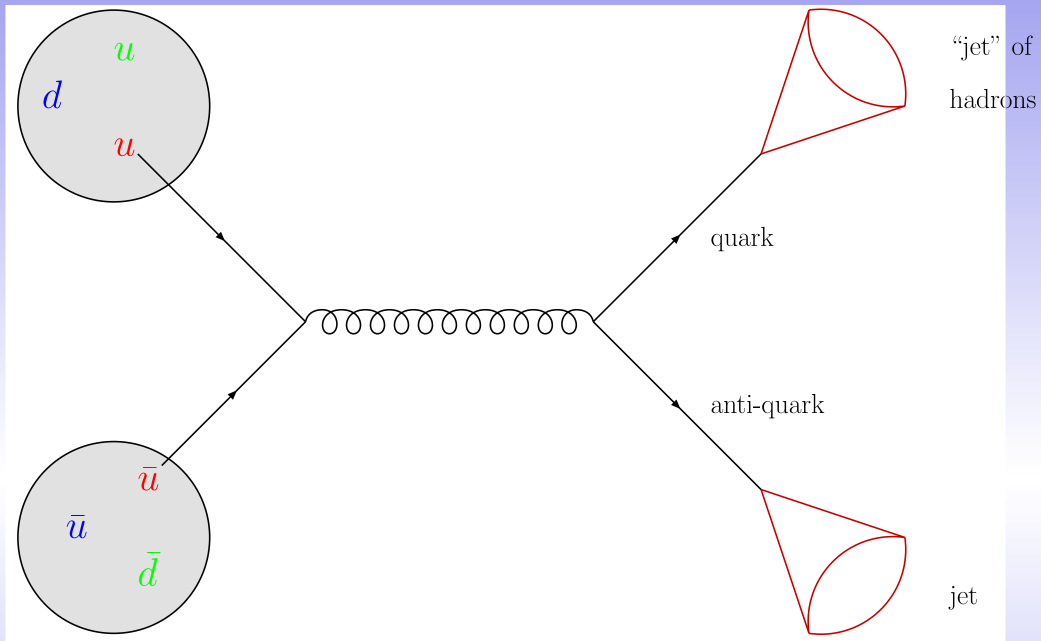
Batavia, Illinois: $p\bar{p}$ collider

Tevatron Run I:
$\sqrt{s} = 1800$ GeV = 1.8 TeV

Tevatron Run II:

$\sqrt{s} = 1.96$ TeV

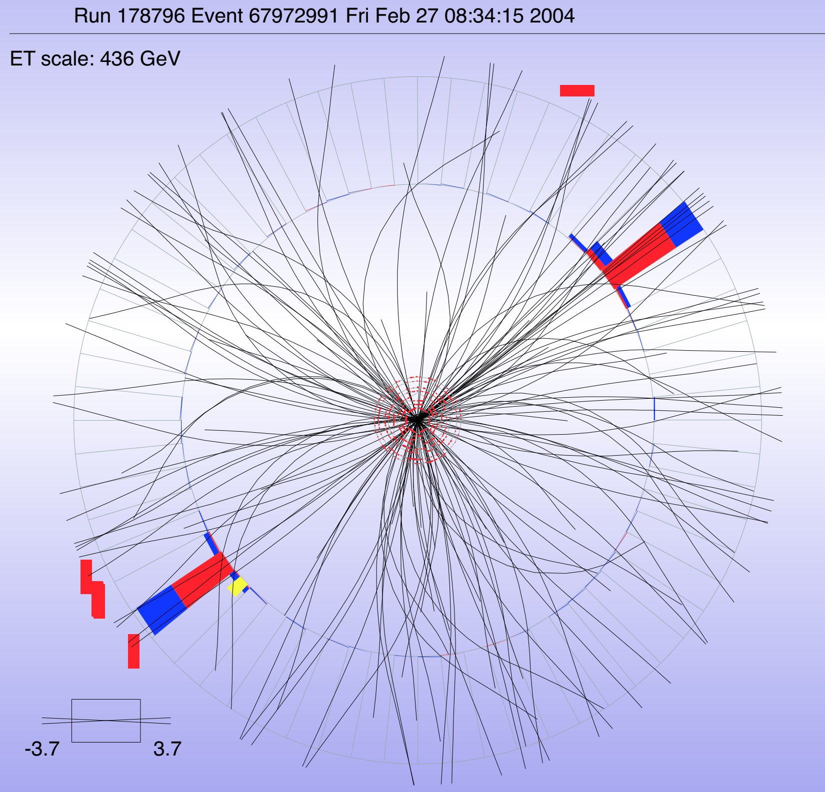
Theoretical picture



- Constituents of the proton and anti-proton collide. Not all of the total energy of the beams is available to them.
- A hard scattering involving quarks and gluons takes place.
- The hard quarks and gluons (carrying large momenta) evolve into "jets" which contain large numbers of light hadrons and are observed in the detectors of the experiment.

A real event

- An event from the D0 experiment at the Fermilab Tevatron:

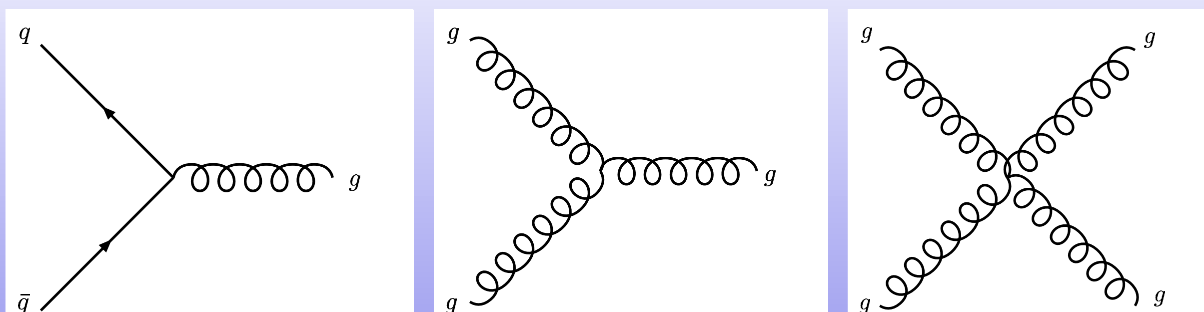


- Two jets of hadrons are produced back-to-back, signified by the energy deposits in the outer calorimeters.

Feynman diagrams

- The physics of the quarks and gluons is described by a quantum field theory, named Quantum Chromodynamics (QCD).
- This theory can be visualized in terms of Feynman diagrams. These diagrams can be built up from a basic set of rules, derived from the Lagrangian of the theory, that summarize the particle content and interactions of QCD.

propagation of a gluon or a quark

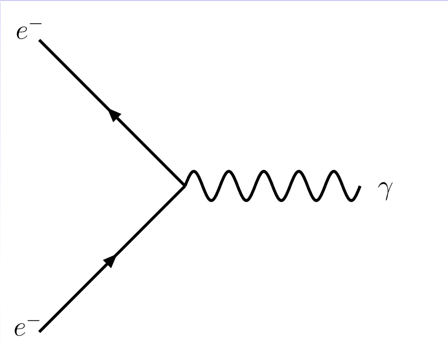


interactions between quarks and gluons

- In these diagrams, momentum and charge conservation occurs at each vertex

Perturbation theory

- Each interaction involves a coupling that measures its strength. For example the coupling between photons and electrons in QED:



coupling constant e related to the fine-structure constant $\alpha = \frac{e^2}{4\pi}\left(\frac{1}{\epsilon_0 \hbar c}\right)$

- The diagrams built up from these interactions represent approximations of the full theory that we are unable to solve directly or exactly.
- Instead, one solves as a perturbative expansion in the interaction strength g. For instance, one calculates an amplitude $\mathcal{M}$ related to an observable that we want to measure as:

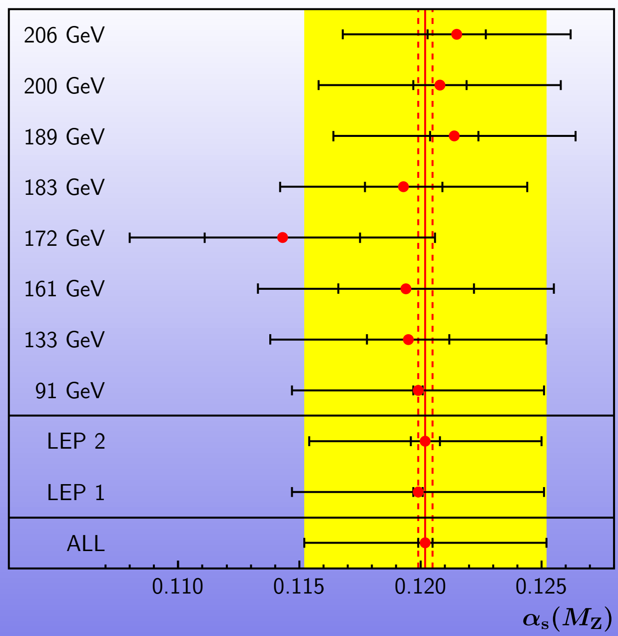
$$\mathcal{M} = \mathcal{M}_0 + g\mathcal{M}_1 + g^2\mathcal{M}_2 + \ldots$$

Perturbative QCD

- In order to calculate actual physical quantities such as production and decay rates of particles, these amplitudes have to be "squared" in the usual quantum mechanical way:

$$|\mathcal{M}|^2 = |\mathcal{M}_0|^2 + g^2\left(|\mathcal{M}_1|^2 + 2\mathcal{M}_0\mathcal{M}_2^\dagger\right) + \ldots$$

- In QED: $g^2 \to \alpha \sim 1/100$ so the perturbative expansion is under good control and theoretical precision is spectacular.



- ⋆ In QCD: $g^2 \to \alpha_s$.
- ⋆ Precision experiments over many years, for example at LEP, have measured $\alpha_s = 0.12$.
- ⋆ This means that the perturbative expansion is not as good for QCD.

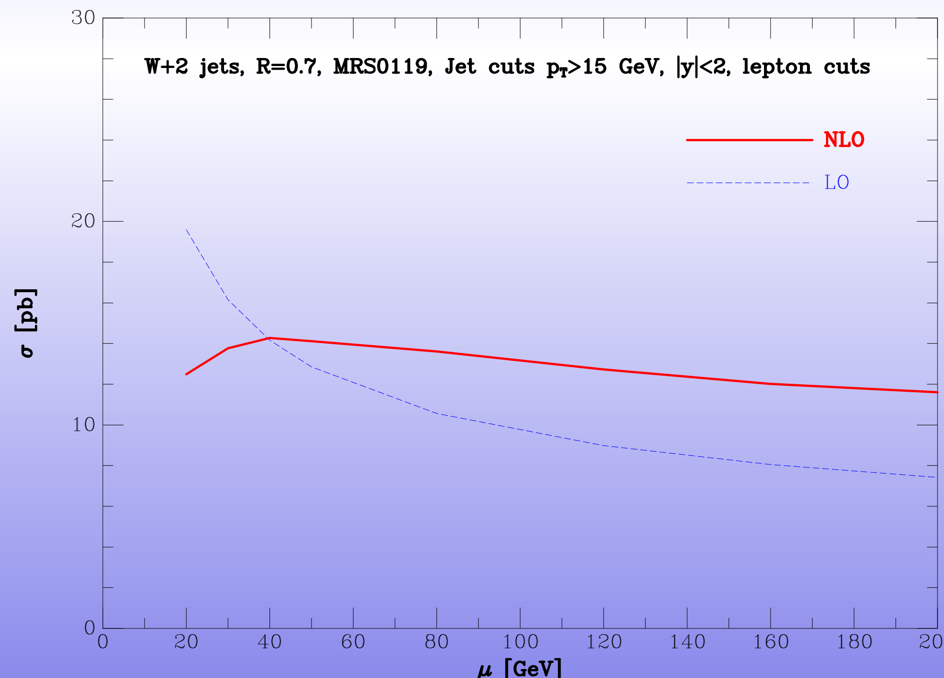
Scale dependence

- Moreover, in order to properly define our perturbation theory so that it makes sense at every order of the expansion, it is necessary to introduce a parameter μ that has the dimensions of mass. It is artifical in that it does not exist in the full theory.

⋆ Full theory: no dependence on μ

⋆ First approximation ($|\mathcal{M}_0|^2$): a good description of the essential physics, but there's substantial μ-dependence and little information on the absolute values of physical quantities

⋆ Next approximation ($\mathcal{O}(\alpha_s)$): dependence on μ is greatly reduced and the normalization is well-controlled
"next-to-leading order" (NLO)

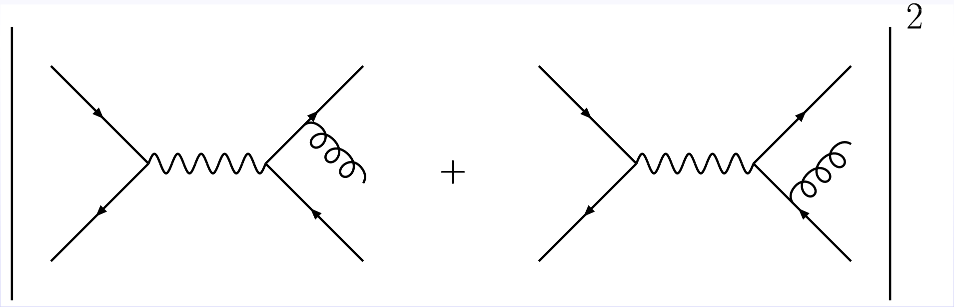


Next-to-leading order diagrams

- As indicated in the expansion, there are two types of next-to-leading order contribution:

$$|\mathcal{M}_1|^2 + 2\mathcal{M}_0\mathcal{M}_2^\dagger$$

- The first term just corresponds to the radiation of an additional strongly interacting particle, for instance:



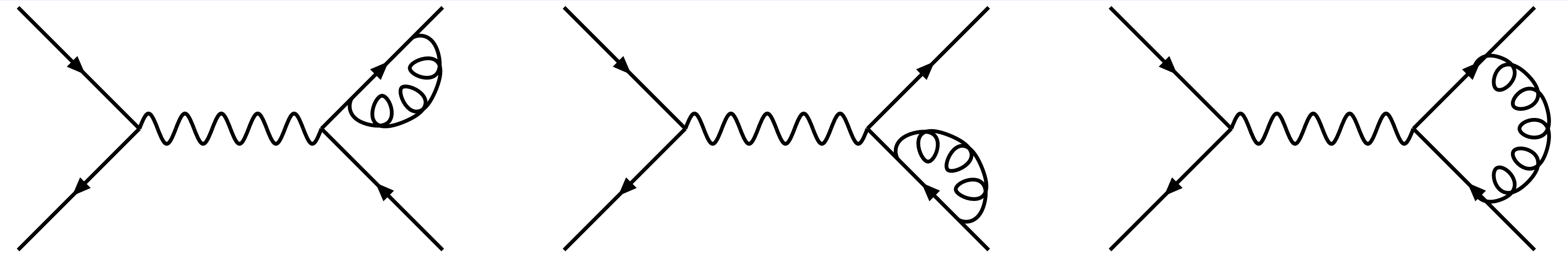
$$\sim \quad g_s \times g_s \quad \sim \quad \alpha_s$$

- These contributions are termed “real” emission diagrams. Their inclusion begins to model more accurately kinematic effects, since we know that in the end we observe jets composed of many individual particles.
- Diagrams are easy to calculate, limited only by computer power.

Next-to-leading order diagrams

$$|\mathcal{M}_1|^2 + 2\mathcal{M}_0\mathcal{M}_2^\dagger$$

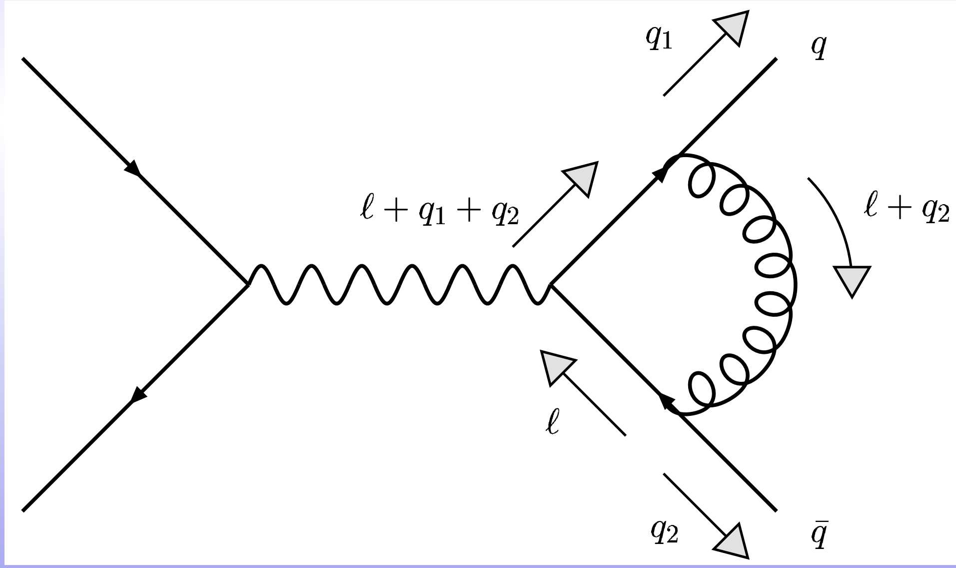
- The other contribution is an interference effect between the lowest order diagrams ($\mathcal{M}_0$) and a new class, $\mathcal{M}_2$:



- A gluon is emitted from a quark and reabsorbed by the same, or a different, quark.
- These are called "virtual" diagrams and have the same kinematics as the lowest order contribution. Calculating their contribution can be highly non-trivial.

Loop diagrams

- Another name for these contributions is “loop” diagrams.
- Momentum conservation at each vertex means that we can introduce an arbitrary momentum transfer ℓ that circulates around the loop:

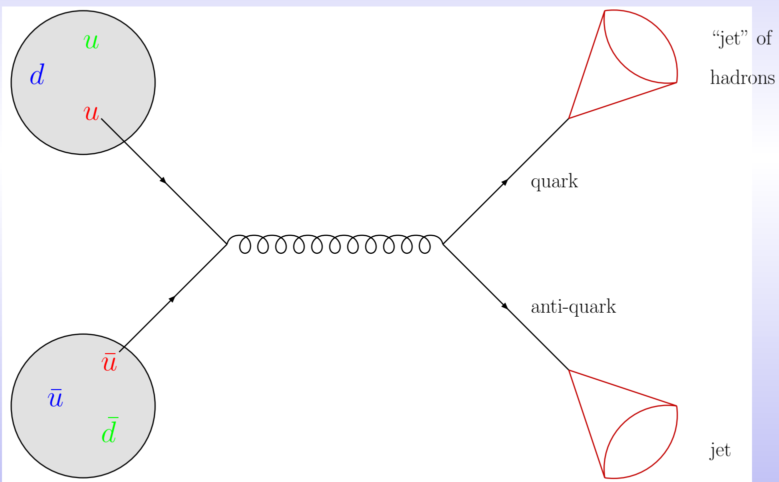


quark has momentum q_1 and anti-quark q_2, so the intermediate Z^0 has momentum $q_1 + q_2$

- Contributions from all values of ℓ should be included, so a “loop integral” over it must be performed.

Calculational difficulties

- It is hard to evaluate the loop integrals analytically as a function of all the particle masses. It is easiest to perform the calculations using various convenient approximations.



- ⋆ the quarks inside the (anti-)proton have masses $\sim$ MeV $\ll 1$ GeV
- ⋆ the energy of a typical jet of hadrons is ~ 20 GeV
- ⋆ if a top quark is produced, its mass is ~ 175 GeV

- Moreover, for more complicated collisions that produce four or more particles, no complete calculation of the virtual diagrams exists. This is an active area of research.

General purpose NLO

- As a result of the complicated calculations required, there has been a proliferation of numerical codes that compute NLO corrections.
- Some of the results in the literature cannot be reproduced by an interested physicist who wants to obtain predictions for a new set of experimental conditions.
- It would be useful to have a general purpose tool that streamlines the calculation of NLO corrections for today's colliders
  $\longrightarrow$ hadron colliders (the Tevatron and the LHC, soon)
  - ⋆ take advantage of modern techniques so that theoretical results can be recycled and new calculations are easy to add;
  - ⋆ provide a freely available tool that can be used by experimenters to compare with data. Calculations based on new values of physical parameters and selection cuts are easily performed.

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

Theoretical status

Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 2j$	$WW+\leq 0j$	$WWW+\leq 3j$	$t\bar{t}+\leq 0j$
$W+b\bar{b}+\leq 0j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 0j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 2j$	$ZZ+\leq 0j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 0j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 0j$
$Z+c\bar{c}+\leq 0j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 0j$
$\gamma+\leq 1j$	$\gamma\gamma+\leq 1j$		$b\bar{b}+\leq 0j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 0j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 0j$		
	$Z\gamma+\leq 0j$		

Overview of MCFM

Overview

- Downloadable general purpose NLO code, "MCFM" JC and R.K. Ellis
  (+F. Tramontano, +F. Maltoni, S. Willenbrock)

$p\bar{p} \to W^\pm/Z$	$p\bar{p} \to W^+ + W^-$
$p\bar{p} \to W^\pm + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^\pm + \gamma$	$p\bar{p} \to W^\pm/Z + H$
$p\bar{p} \to W^\pm + g^\star\ (\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W^\pm/Z +$ 1 jet	$p\bar{p} \to W^\pm/Z +$ 2 jets
$p\bar{p}(gg) \to H$	$p\bar{p}(gg) \to H +$ 1 jet
$p\bar{p}(VV) \to H +$ 2 jets	$p\bar{p} \to t + q$
$p\bar{p} \to H + b$	$p\bar{p} \to Z + b$

- Knowledge of these processes at NLO provides the first precise predictions of their event rates, which is used in various ways.
  - ⋆ production of pairs of W's and Z's: the structure of the weak interaction at high energy
  - ⋆ W and H production: possibly the first hint of a Higgs boson at the Tevatron
  - ⋆ $H + 2$ jets: an important discovery mode at the LHC

Comparison with other approaches

- There are generic routines for handling common tasks, so that implementing new processes is “painless”
- Emphasis has been on bringing together calculations of signals and backgrounds for particularly challenging searches, so that NLO effects may be more easily studied with just one code
- Where possible, appropriate decays of vector bosons are included and all possible spin correlations are retained for a better assessment of the effect of experimental cuts
  - $\ominus$ low particle multiplicity (no showering)
  - $\ominus$ no hadronization
  - $\ominus$ hard to model detector effects
  - $\oplus$ less sensitivity to μ
  - $\oplus$ rates are better normalized
  - $\oplus$ fully differential distributions

MCFM Information

- Version 4.1 available at:

  `http://mcfm.fnal.gov`

- Improvements over previous releases:

  - ⋆ more processes
  - ⋆ better user control
  - ⋆ separate variation of factorization and renormalization scales
  - ⋆ support for PDFLIB, Les Houches PDF accord ($\longrightarrow$ PDF uncertainties)
  - ⋆ ntuples as well as histograms
  - ⋆ unweighted events
  - ⋆ basic event generator interface
  - ⋆ 'Behind-the-scenes' efficiency

suitable for
LO calculations

Technical details: subtraction method

- Methods for dealing with singular regions are well-developed, such as phase-space slicing and dipole subtraction
- MCFM uses the dipole subtraction method, which makes a careful choice of the kinematics in the subtraction terms to improve the cancellation of singularities

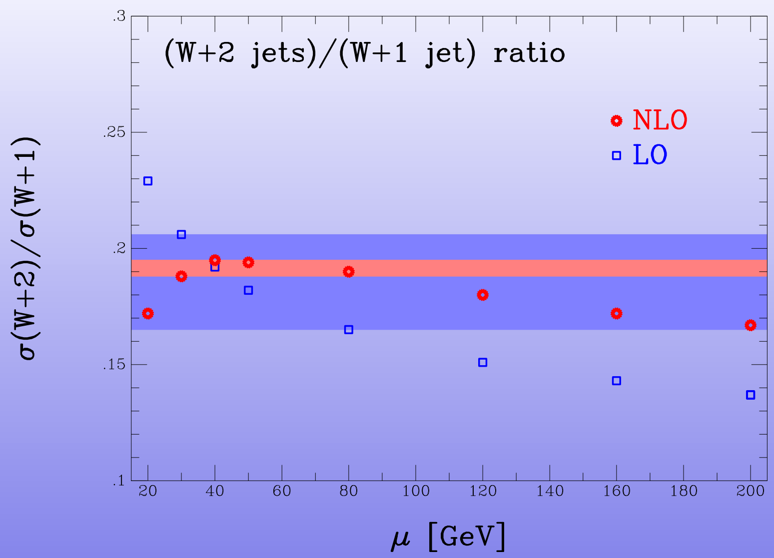
  Catani, Seymour
- However, for high multiplicity final states, the number of singular regions is large, resulting in:
  - ⋆ Very many dipoles, each with their own set of kinematics
  - ⋆ Time-consuming calculation of subtraction terms
- Modifications to the original formalism have been implemented in MCFM. The subtraction region can be limited in order to speed up the code and also to improve numerical stability

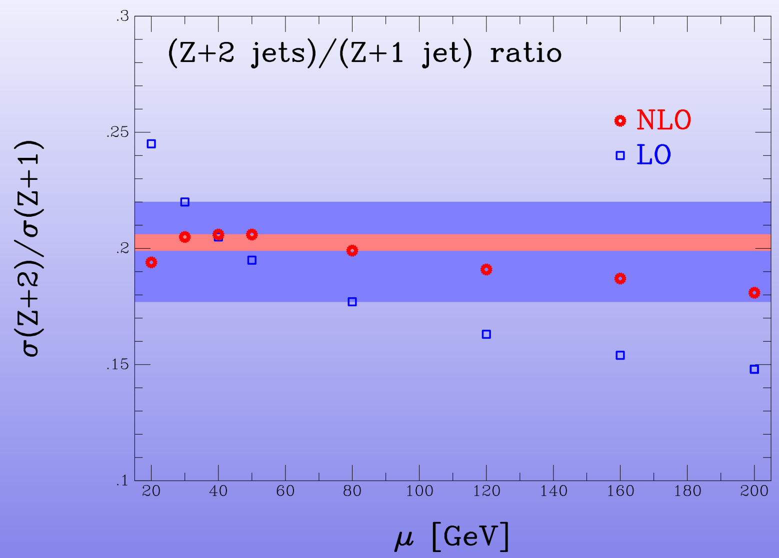
  Z. Nagy, hep-ph/0307268

W/Z+jets cross-sections

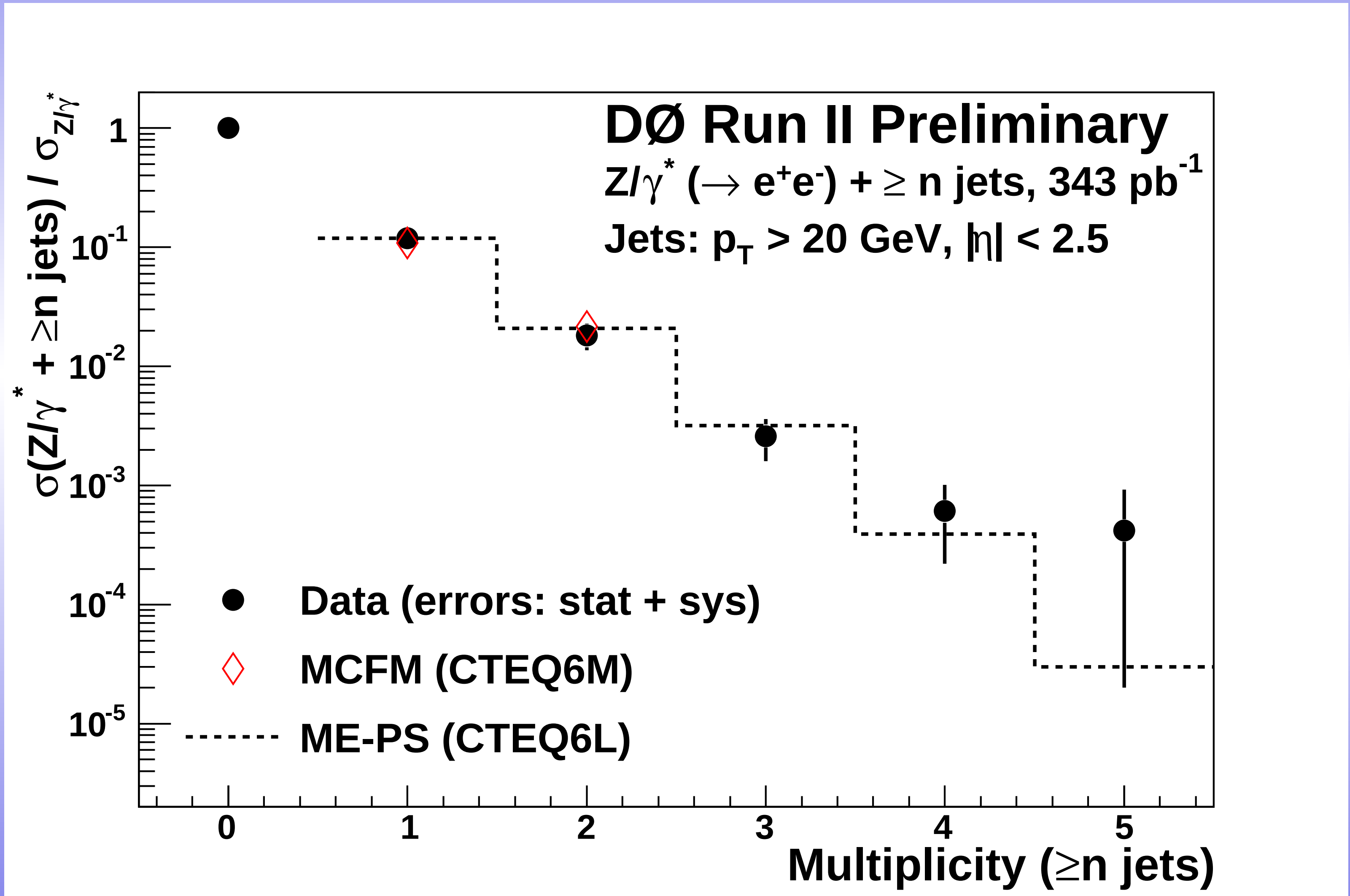
Rates at the Tevatron

- The $W/Z + 2$ jet NLO calculation is the most complicated (time-consuming) process currently implemented. This is due to both the lengthy virtual matrix elements (vector boson $+ 4$ partons) and the complicated structure of phase space.
- The usual features such as reduced scale dependence are observed, e.g. the theoretical prediction for the number of events containing 2 jets divided by the number with only 1 is improved.



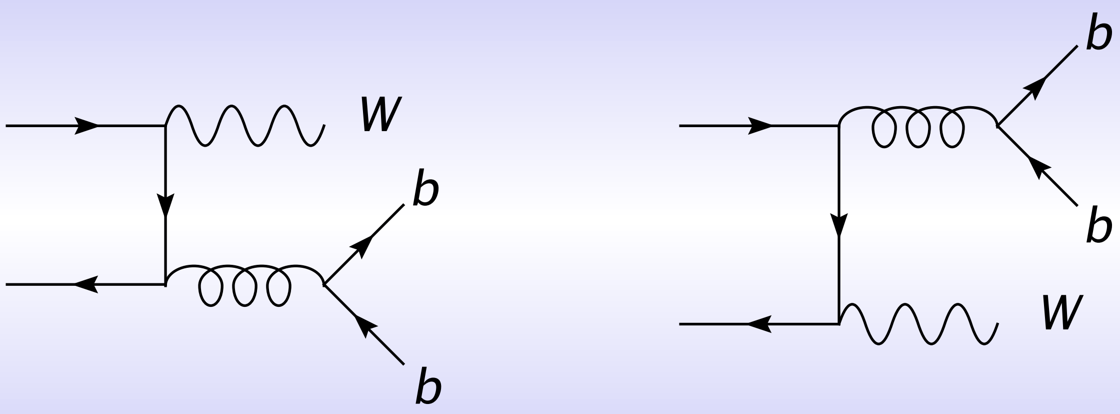


Preliminary data



Vector boson + heavy flavour

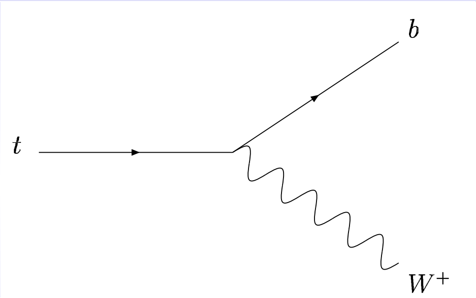
- In lowest order bottom quark pairs are produced in association with W's by gluon splitting alone:



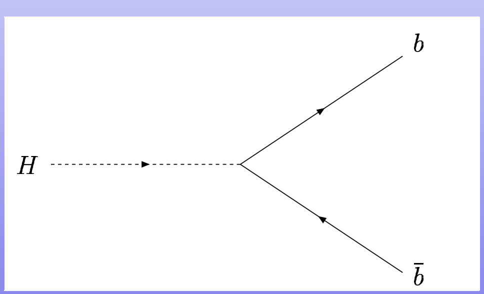
- Beyond LO, the b-quark is treated as a massless particle in MCFM
  - ⋆ a finite cross-section requires a cut on the b-quark p_T
  - ⋆ this means that this calculation is not suitable for estimating the rate with only a single b tag

Heavy flavour as a background

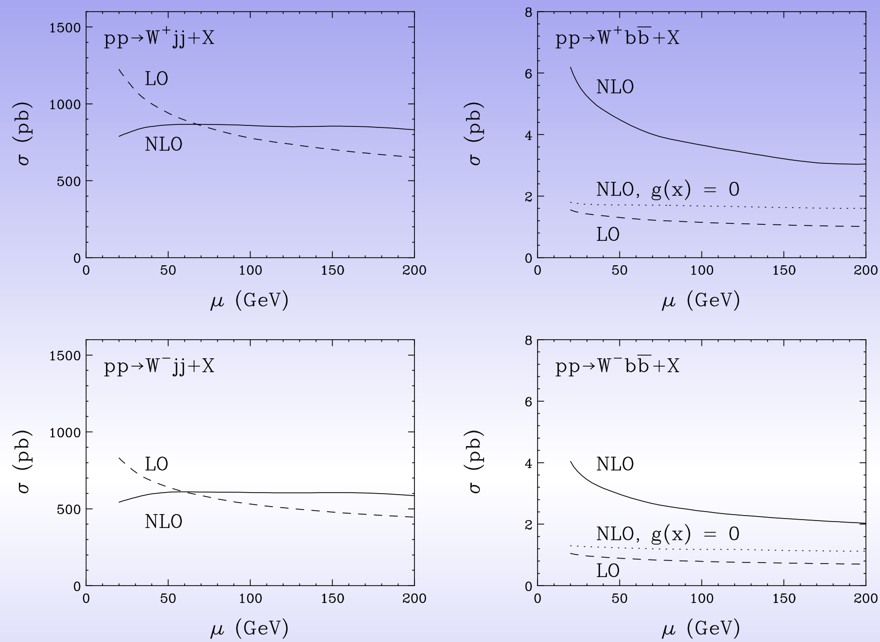
- Events containing jets that are heavy-quark tagged are important for understanding both old and new physics:
  - ⋆ Top decays $t \to W + b$



  - ⋆ Much new physics couples preferentially to massive quarks, for instance a light Higgs with $m_H < 140$ GeV decaying to $b\bar{b}$

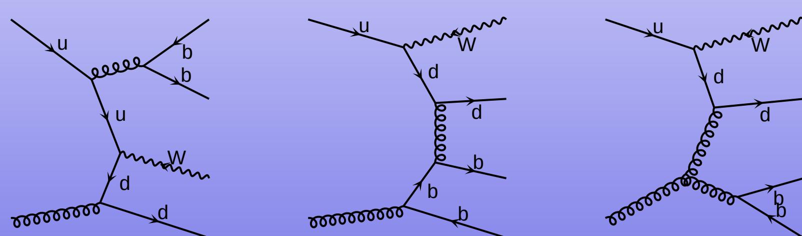


Jets and heavy flavour at the LHC



- The large gluonic contribution appearing in $Wb\bar{b}$ for the first time at NLO results in a huge correction and poor scale dependence.

Diagrams by MadGraph



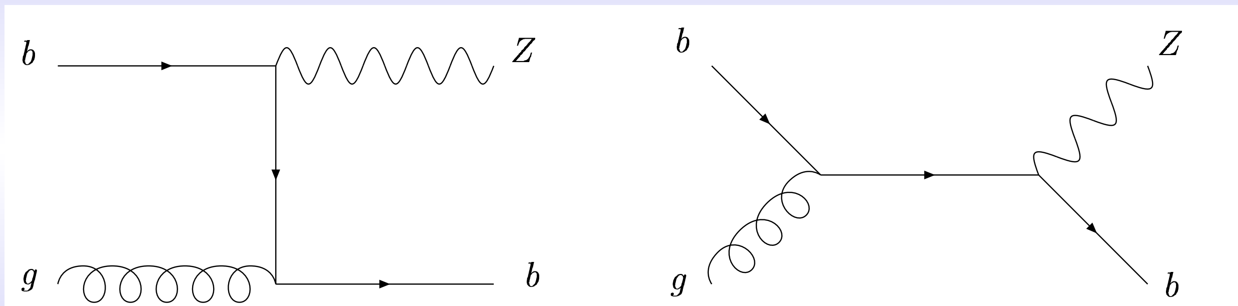
(a) (b) (c)

Single-tagged heavy flavour

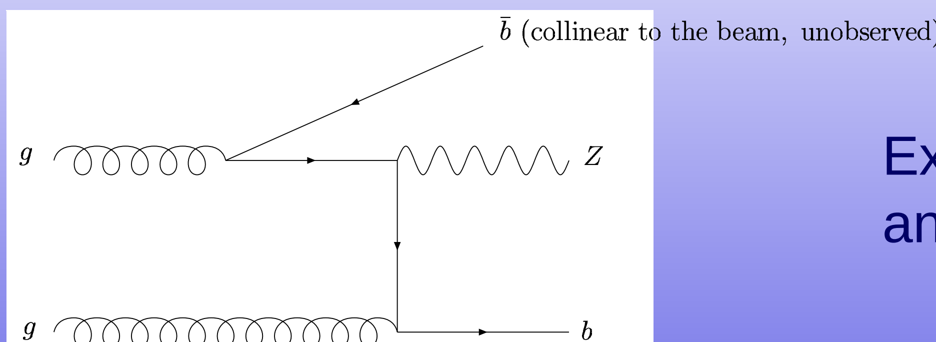
JC, Ellis, Maltoni, Willenbrock

Heavy flavour fraction revisited

- Often the presence of two b-quarks in the final state is actually only inferred from a single b-tag
- In this case, there is another way of computing the theoretical cross-section. For instance, in the case of $Z+$ heavy flavour:



- Requires knowledge of b-quark pdf's, but compare to:



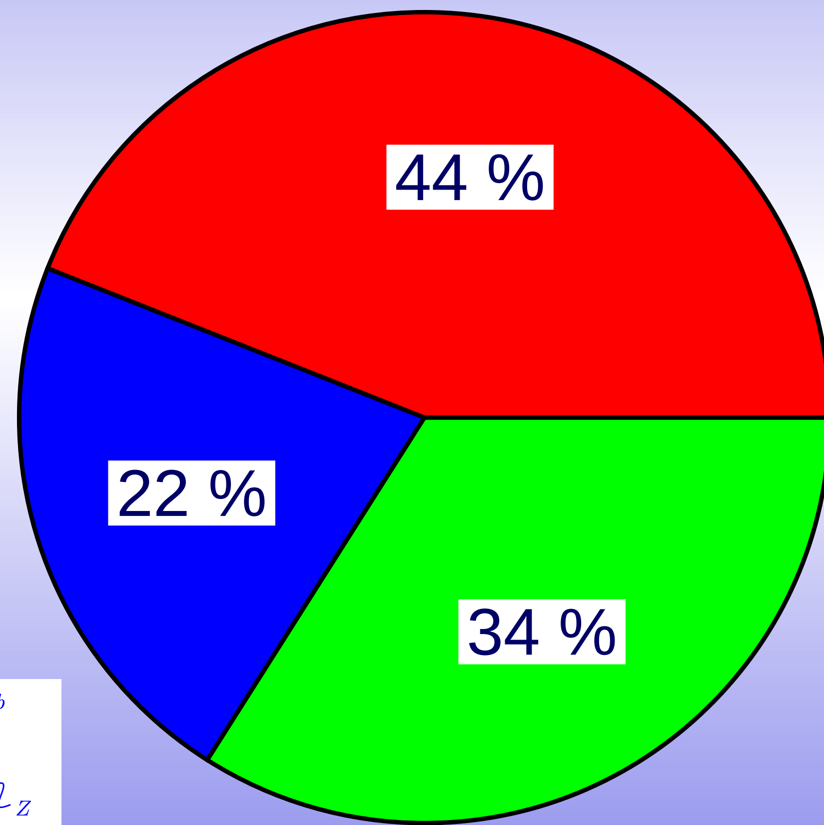
Expansion in $\alpha_s \ln(M_Z/m_b)$ and NLO calculation difficult

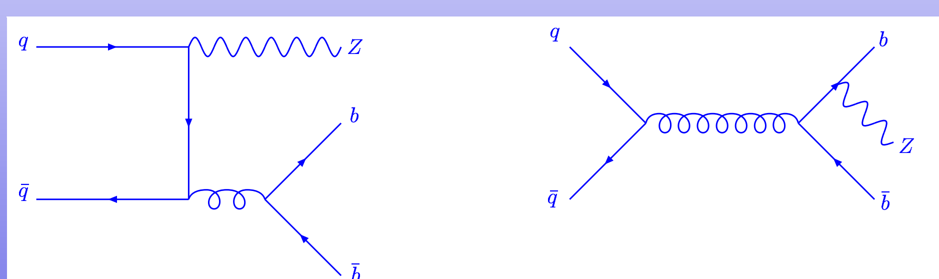
$Z + b$ at NLO - Run II

JC, K. Ellis, F. Maltoni and S. Willenbrock, hep-ph/0312024

- $p_T^{\text{jet}} > 15$ GeV, $|\eta^{\text{jet}}| < 2$
- $\sigma(Z + \text{ one } b \text{ tag}) = 20$ pb
- Fakes from $Z+$ jet events are significant
- Prediction for ratio of $Z + b$ to untagged $Z + \text{jet}$ is

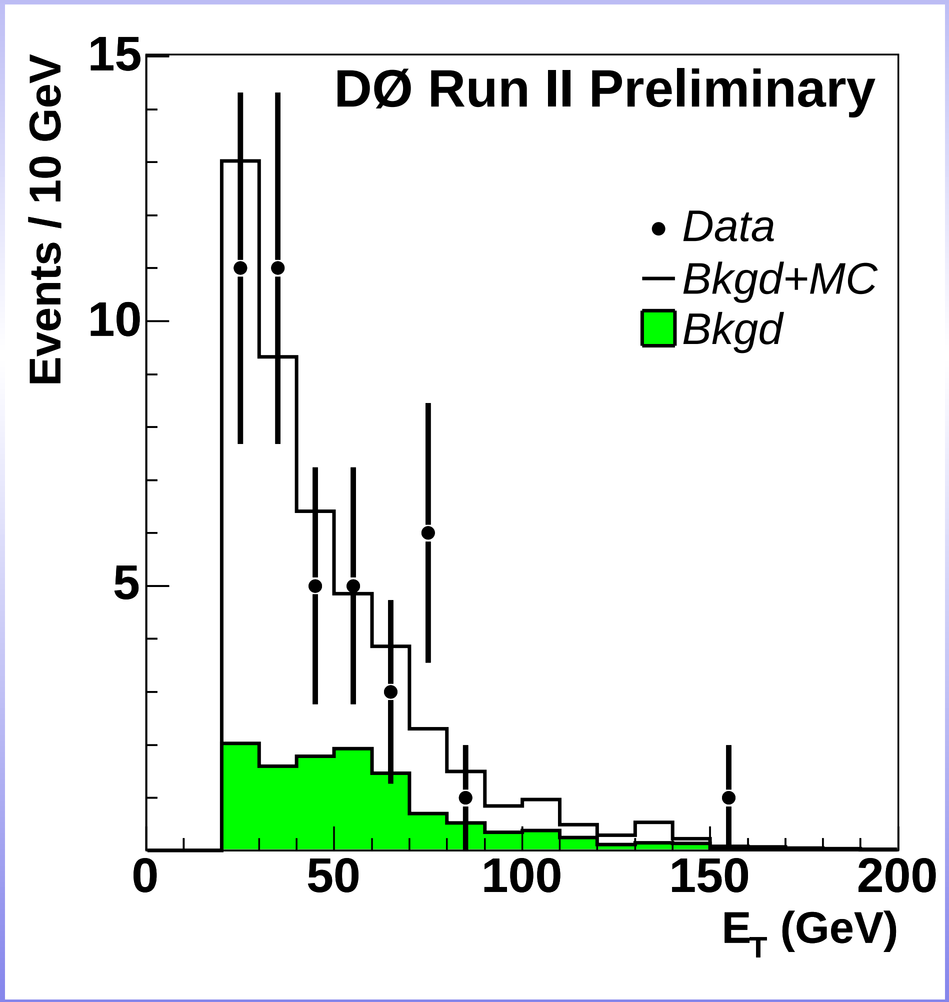
  0.02 ± 0.004





Experimental result

- Based on $189\ \mathrm{pb}^{-1}$ of data from Run II



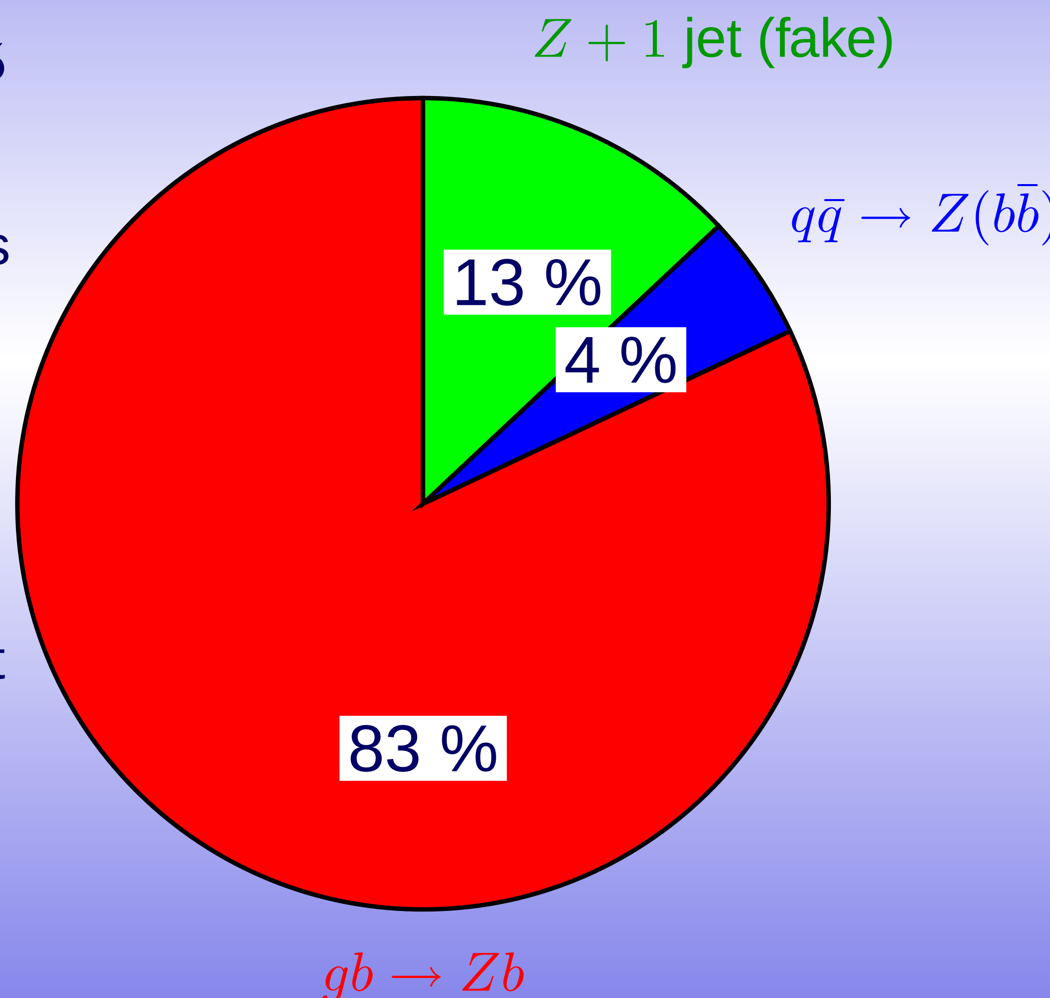
Ratio of cross-sections:

$$\frac{\sigma(Z+b)}{\sigma(Z+j)} = 0.024 \pm 0.007$$

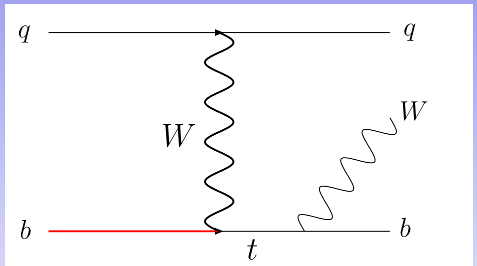
compatible with the NLO prediction from MCFM

LHC expectations

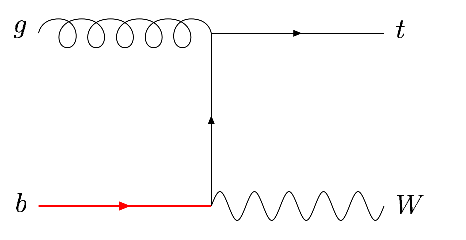
- $p_T^{\rm jet} > 15$ GeV, $|\eta^{\rm jet}| < 2.5$
- $\sigma(Z + \text{ one } b \text{ tag}) = 1$ nb
- Fakes from $Z+$ jet events are much less significant and $q\bar{q}$ contribution is tiny
- This should allow a fairly clean measurement of heavy quark PDF's (currently, only derived perturbatively)



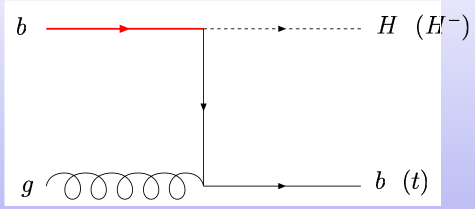
b-PDF uses



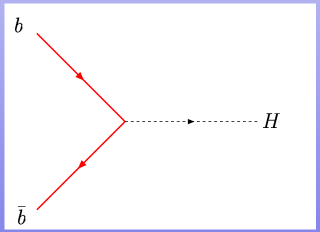
single-top $qb \to qWb$



single-top $gb \to tW$



(charged) Higgs+b



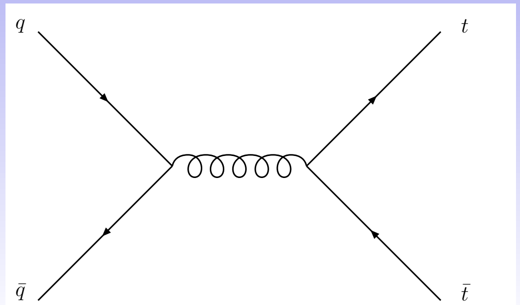
inclusive Higgs

Single top production and decay

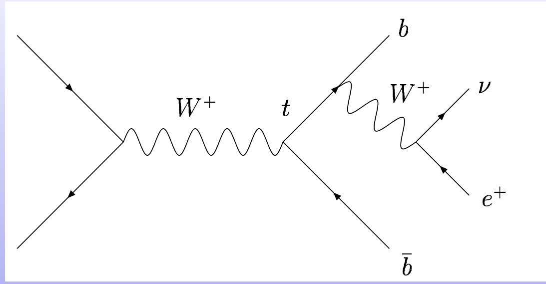
JC, Ellis, Tramontano

Producing the top quark

- The top quark was discovered in Run I of the Tevatron by producing it in pairs:

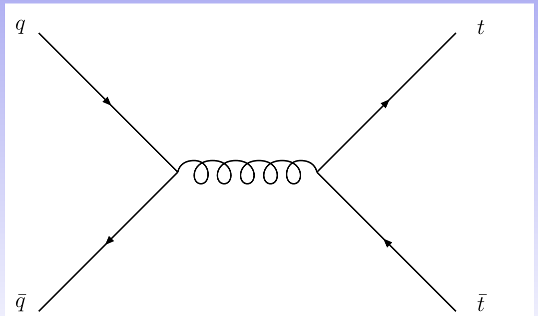


- However, it should also be possible to produce it singly in Run II, for example:

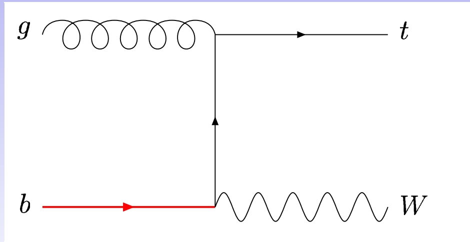


- This is especially interesting since it would yield information about the weak interaction of top quarks (V_{tb}).

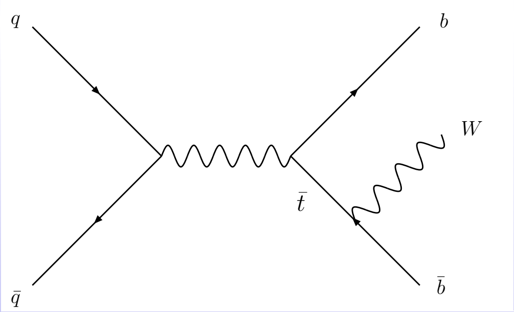
Top production rates



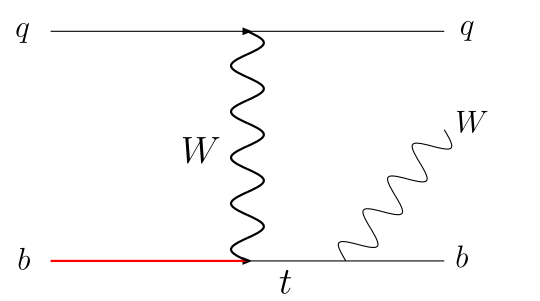
6 pb
720 pb



0.08 pb
50 pb



0.8 pb
10 pb

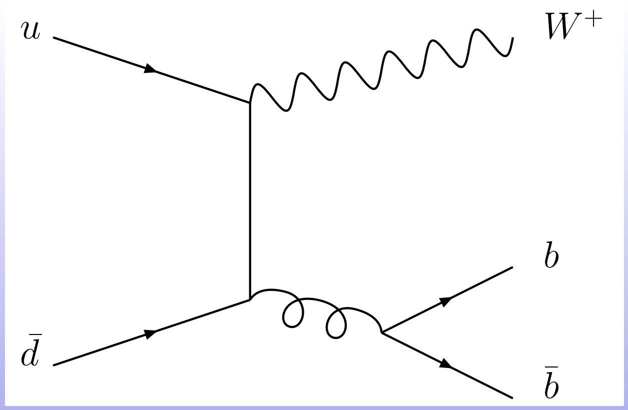


1.8 pb
240 pb

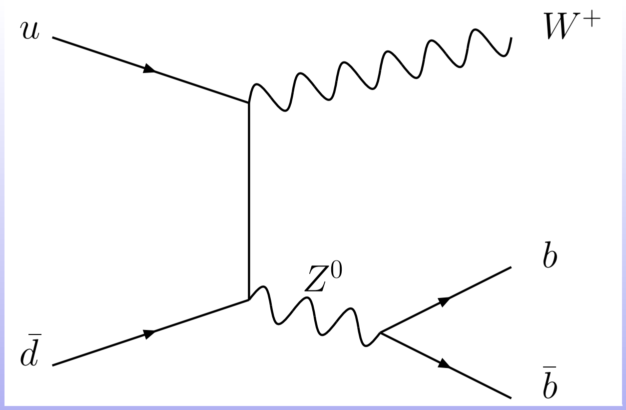
- All cross-sections are known to NLO (Tevatron / LHC)
- The total single top cross-section is smaller than the $t\bar{t}$ rate by about a factor of two, at both machines

Experimental signature

- The experimental “signature” is an event which contains a top quark – identified by the combined mass of its decay products – and which also has two jets containing b-quarks. These can be distinguised from other jets around 50% of the time.
- Observed events such as these can also be the result of other basic processes. These backgrounds include, for example:



$Wb\bar{b}$

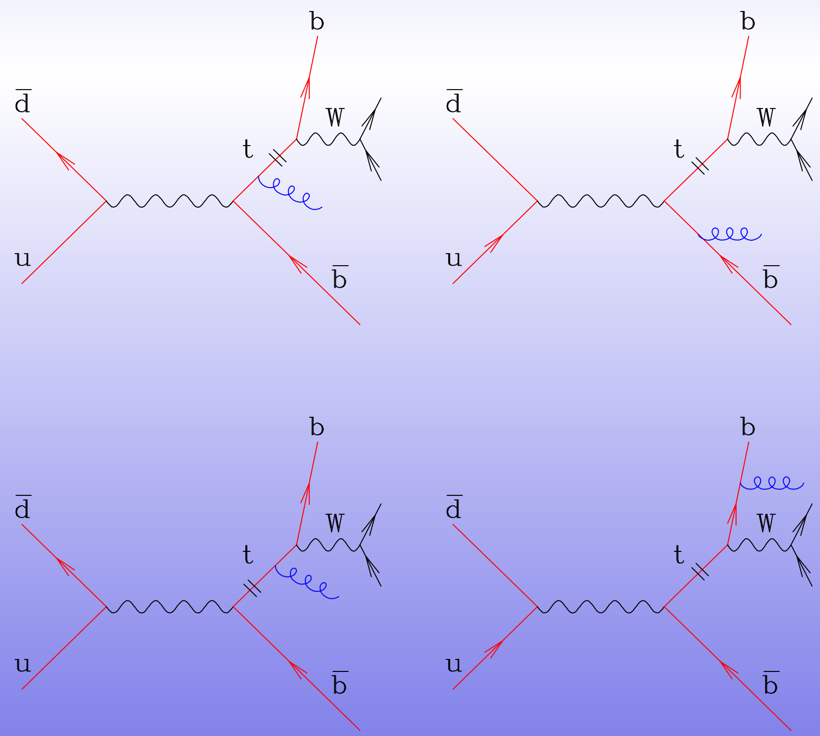


$WZ(\to b\bar{b})$

- MCFM can calculate the signal and backgrounds at NLO.

Inclusion of decay

- Results had previously been presented without including the decay of the top quark. Without it, predictions for some quantities used in Tevatron search strategies are impossible
- Final state radiation that enters at next-to-leading order is possible in either the production or decay phase:

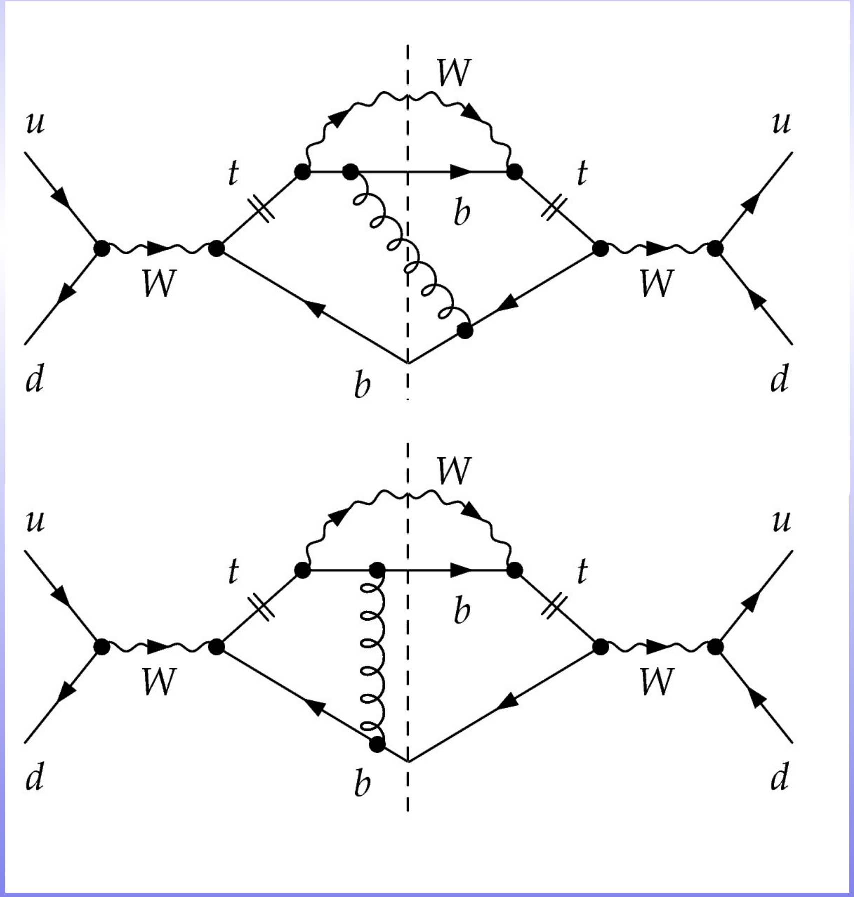


production

decay

On-shell approximation

- Such a division is only possible assuming that every diagram has one top quark on its mass-shell, neglecting $\mathcal{O}(\Gamma_t/m_t)$ effects
- Contributions not included are interferences of the form:



real

virtual

Justification

Fadin, Khoze, Martin
Melnikov, Yakovlev

- Characteristic time scale for production of the top quark is of order $1/m_t$, whereas the time for the decay is $1/\Gamma_t$
- In general, these stages are well-separated and interference effects average to zero
- If the gluon is soft, this argument is not sufficient
- However, in this region real and virtual radiation must cancel so that this phase space is not especially enhanced. In order for the propagator to stay resonant, the gluon energy must be of $\mathcal{O}(\Gamma_t)$
- For IR-safe variables, interference effects should be $\mathcal{O}(\alpha_s \Gamma_t / m_t)$
- Quantitatively confirmed for the s-channel process and for $t\bar{t}$ production in e^+e^- annihilation Pittau; Macesanu

Implementation in MCFM

- Uses the extension of the dipole method to handle massive particles Catani, Dittmaier, Seymour, Trocsanyi
- Extra subtraction term to deal with radiation in the decay of the top quark
  - ⋆ Real process containing soft and collinear singularities

$$t \longrightarrow W + b + g$$

  - ⋆ Counter-term

$$t \longrightarrow \widetilde{W} + \tilde{b}$$

  - ⋆ Since the W is implemented with a Breit-Wigner, we use a Lorentz transformation which ensures that $\tilde{p}_W^2 = p_W^2$ and also ensure that the b-quark remains massless $\tilde{p}_b^2 = p_b^2 = 0$

JC, Ellis, Tramontano

Results

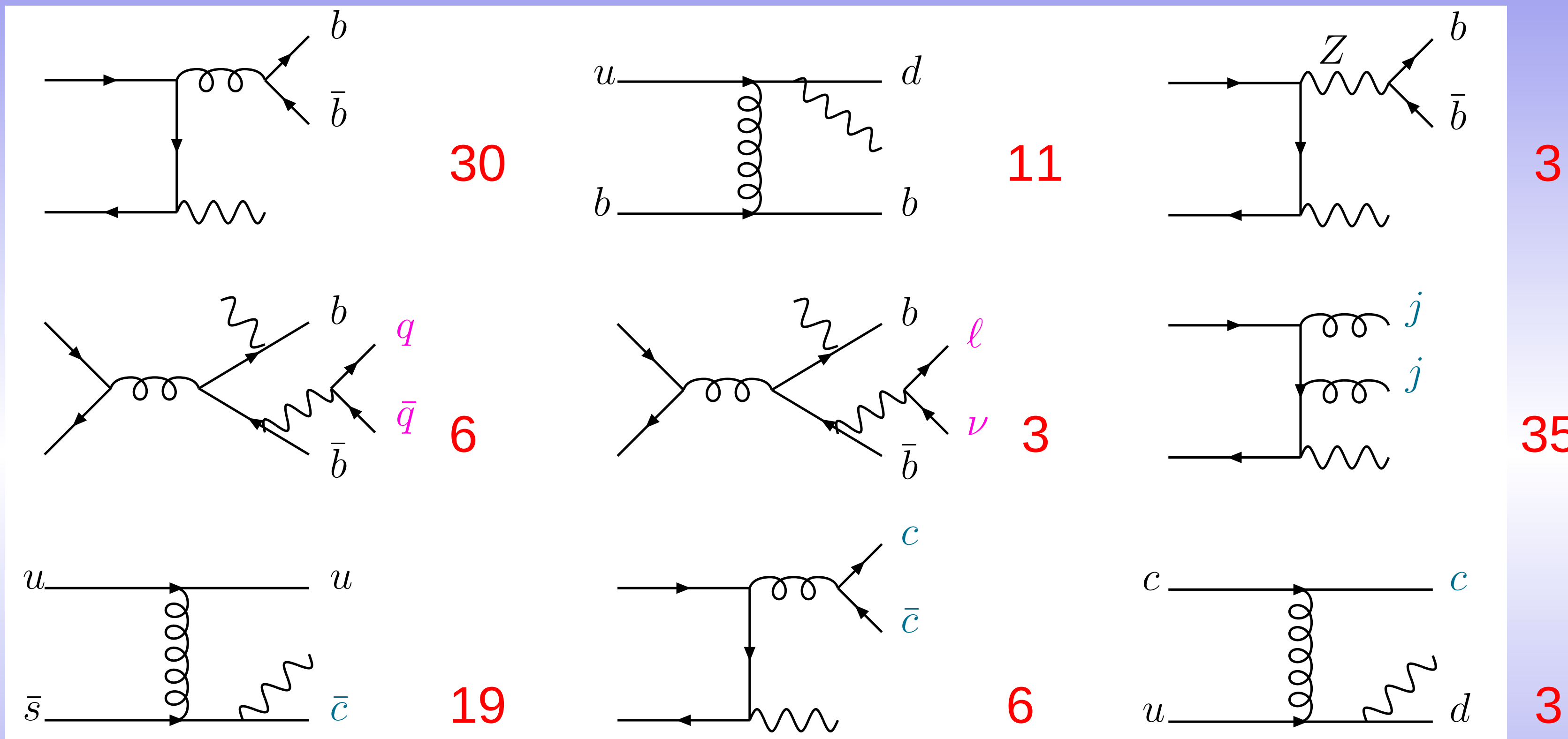
- Parton level study of the Tevatron single top analysis performed by CDF

Lepton p_T	$p_T^e > 20$ GeV
Lepton pseudorapidity	$\lvert\eta^e\rvert < 1.1$
Missing E_T	$\not{E}_T > 20$ GeV
Jet p_T	$p_T^{\text{jet}} > 15$ GeV
Jet pseudorapidity	$\lvert\eta^{\text{jet}}\rvert < 2.8$
Mass of $b + l + \nu$	$140 < m_{bl\nu} < 210$ GeV

- The inclusion of radiation in the decay lowers the (exclusive two-jet) cross-section slightly:

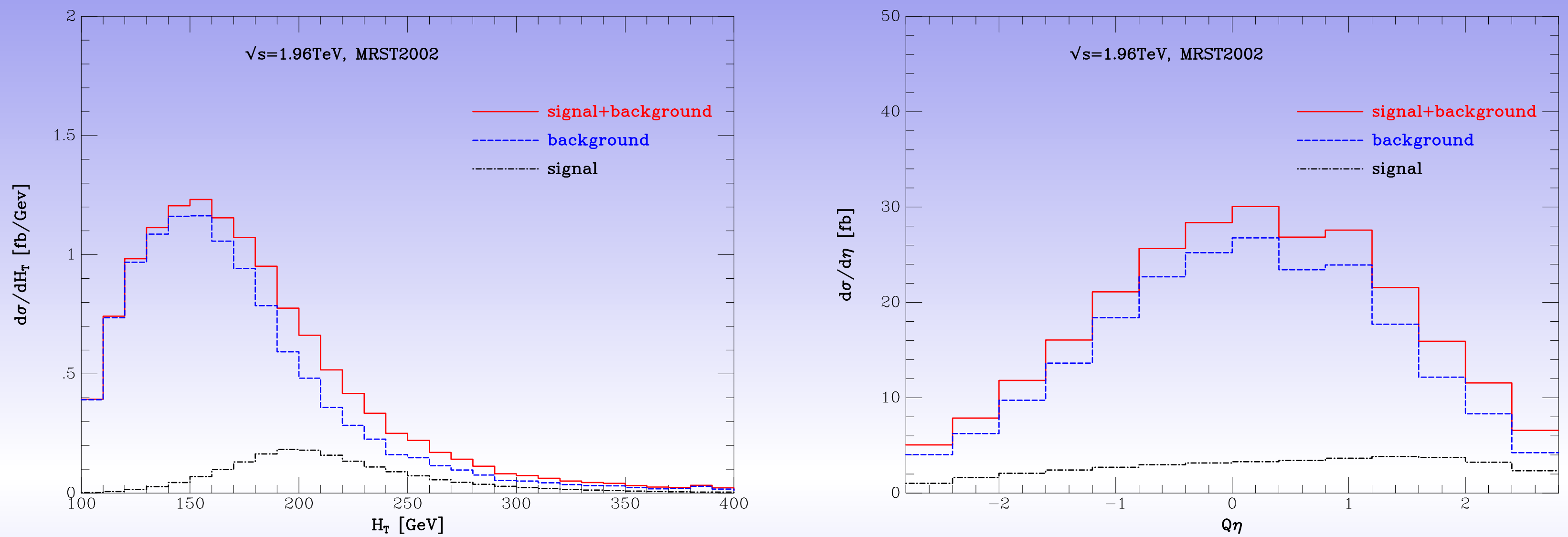
Process	σ_{LO} [fb]	σ_{NLO} [fb]
s-channel single top	10.3	11.7
s-channel (with decay radiation)	10.3	11.3
t-channel single top	38.8	29.4
t-channel (with decay radiation)	38.8	26.6

Backgrounds



- Cross-sections in fb include nominal tagging efficiences and mis-tagging/fake rates. Calculated with MCFM, most at NLO
- Rates are 7 fb and 11 fb for s- and $t-$channel signal

Single top signal vs. backgrounds



- $H_T =$ scalar sum of jet, lepton and missing E_T
- $Q\eta$ is the product of the lepton charge and the rapidity of the untagged jet, useful for picking out the t-channel process
- Signal:Background (with our nominal efficiencies) is about $1:6$ – a very challenging measurement indeed. Production in this mode has not yet been observed at Fermilab.
- Knowing the characteristics of signal and background events at NLO should help this search.

Bowen, Ellis, Strassler, hep-ph/0412223

Shortcomings

The approach in MCFM involves a number of approximations:

- The b-quark is massless
  LO calculation with $m_b = 4.75$ GeV $\longrightarrow < 1\%$ effect
- The top quark is put on its mass-shell
  LO calculation with a Breit-Wigner $\longrightarrow 1\%$ effect
- We neglect interference between radiation in production/decay
  qualitative argument for $\mathcal{O}(\alpha_s \Gamma_t / m_t) \sim$ less than a percent
- We assume p_T-independent heavy flavour tagging efficiencies, as well as stable b and c quarks
  easily addressed by a more detailed experimental analysis
  with the publicly-available code
- No showering or hadronization is performed
  no NLO/PS prediction yet available; however the large cone
  size $\Delta R = 1$ should help minimize these effects

Summary

- Events seen in collider physics experiments at Fermilab and CERN can (and will) be described very well with the theory of perturbative QCD.
- However, making an accurate assessment of particle rates and extracting detailed information from the data requires calculations that go beyond the simplest approximation.
- Next-to-leading order calculations are the first step towards precision. However, their difficulty means that there are many interesting analyses which are still not possible at this accuracy.
- This is highlighted at the LHC where, on average, many more particles are produced per collision.
- In parallel with the huge undertakings to further expand the "energy frontier", theorists need to provide ever more generic and accurate predictions to keep pace.
- MCFM is a tool which provides a step in this direction.